Current collapse and the role of carbon in AlGaN/GaN high electron mobility transistors grown by metalorganic vapor-phase epitaxy

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The two deep traps responsible for current collapse in AlGaN/GaN high electron mobility transistors grown by metalorganic vapor-phase epitaxy have been studied by photoionization spectroscopy. Varying the growth pressure of the high resistivity GaN buffer layer results in a change in the deep trap incorporation that is reflected in the observed current collapse. Variations in the measured trap concentrations with growth pressure and carbon incorporation indicate that the deepest trap is a carbon-related defect, while the mid-gap trap may be associated with grain boundaries or dislocations. [DOI: 10.1063/1.1418452]

Nitride-based field-effect transistors (FETs) are of great current interest due to their capability of operating at high power and high frequency. However, the performance of these devices can be limited by the presence of material defects in the FET structures. A defect-related phenomenon of particular concern is current collapse, as this effect reduces the output power achievable by the device. Current collapse occurs when a high drain-source voltage is applied to the device, resulting in the transfer of hot carriers from the conducting channel to an adjacent region of the device structure that contains a high concentration of deep traps.[1–5] The carriers can then become trapped at these defects. The loss of channel carriers and the resulting large transverse electric field[4] lead to a collapse of the dc $I-V$ characteristic, which exhibits a reduced drain current and an increase in the knee voltage.

In this work, we employ the photoionization spectroscopy (PS) technique[3,4] to investigate the trapping centers that cause current collapse in AlGaN/GaN high electron mobility transistor (HEMT) structures grown by metalorganic vapor-phase epitaxy (MOVPE). In these measurements, light incident on the ''collapsed'' device photoionizes the trapped carriers from the traps, leading to a restoration of the drain current. It has been shown[4] that the spectral dependence of this drain current increase reflects the characteristic photoionization spectrum of the trap causing the collapse. This provides a signature of the responsible trap as well as the depth of the trap relative to the band edges.[3] In addition to these spectral measurements, we have also carried out complementary light illumination studies of the dependence of the light-induced drain current increase on the amount of light incident on the device. The results of these studies can be analyzed, using an appropriate model,[4] to extract the areal concentrations and photoionization cross sections of the responsible traps.

Previous PS studies of the GaN metal-semiconductor FET (MESFET) and the AlGaN/GaN HEMT have shown that the traps responsible for current collapse in these structures are located in the high-resistivity (HR) GaN buffer layer.[2–5] We have also observed that current collapse is consistently more problematic when the HR-GaN buffer layer is grown at low growth pressures.[6] This is the same growth condition under which the incorporation of defects into the HR-GaN layer, and in particular carbon impurities,[6–8] is significantly enhanced. Consequently, in this work we have studied the effect of varying the MOVPE growth pressure of the HR-GaN buffer layer on the incorporation of traps causing current collapse in AlGaN/GaN HEMT structures, with a particular emphasis on the role of carbon.

The HEMT structures were grown by MOVPE. A 20 nm AlN nucleation layer was grown on a-plane sapphire substrates, followed by a 3 μm HR-GaN buffer layer. A 25 nm layer of $Al_{0.3}Ga_{0.7}N$ was then grown in order to form the two-dimensional electron gas (2DEG). Four wafers were grown under identical conditions, except for a systematic variation of the HR-GaN growth pressure (65, 150, 200, and 300 Torr), in order to vary the defect incorporation in the layer.[7] The 2DEG associated with these structures exhibited sheet charge densities as high as 1.2×10^{13} cm^{-2} with 300 K Hall mobilities around 1200 cm^2/V s. The source-drain spacing was 2–5 μm and the gate length was 0.5 μm. Further details of the materials growth and device fabrication have been reported earlier.[5] For the optical measurements, monochromatic light was provided by either a Xe arc lamp and a 0.22 m double monochromator or a He–Ne laser.

PS in the HEMT devices was carried out by measuring the drain current of the device after exposure to a high drain-source voltage (15 V). The drain current was measured both in the dark (I_{dark}) and after a measured amount of light illumination (I_{light}). The spectral dependence of the fractional increase in the drain current above the dark level, $(\Delta I/I_{dark})\equiv(I_{light}-I_{dark})/I_{dark}$, properly normalized by the amount of incident light, defines a spectral response function, $S(h\nu)$, that has been shown to reflect the photoionization spectrum of the trap causing the collapse.[3,4] Previously published photoionization data for the GaN MESFET,[3] shown as the open squares in Fig. 1(a), exhibit two broad, below-gap absorptions (labeled Trap1 and Trap2) associated with the photoionization of trapped carriers from two distinct

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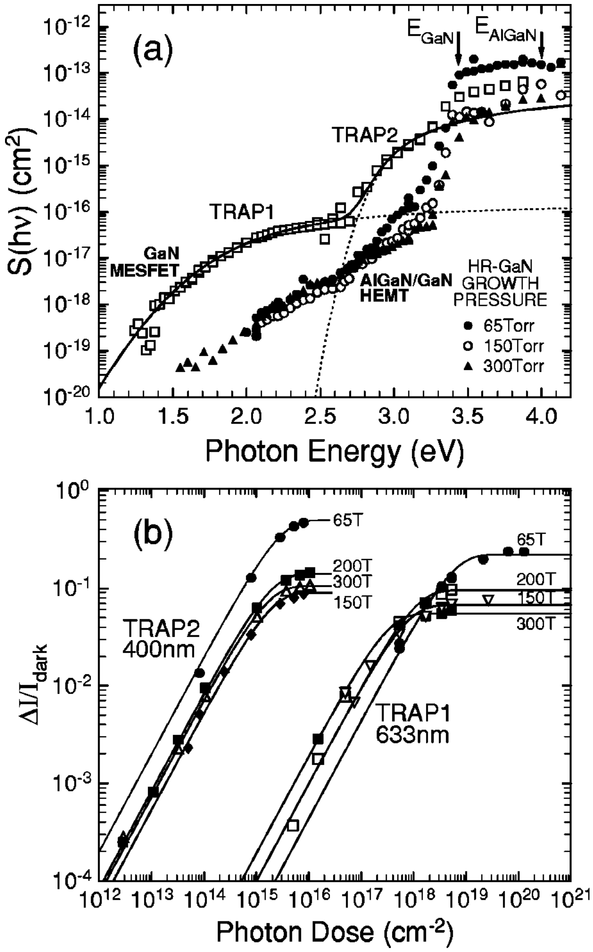

FIG. 1. (a) Photoionization spectra of HEMT structures for three HR-GaN growth pressures (symbols as shown). A GaN MESFET spectrum is shown (open squares) for comparison. (b) Light-induced drain current increase (symbols) as a function of total light illumination for four HEMTs with different HR-GaN growth pressures (65, 150, 200, 300 Torr). The solid lines are fits to the data using a simple model.

electron traps. The rise near the GaN band gap is due to the creation of electron-hole pairs as well as the photoneutralization of negatively charged shallow acceptors. Fitting the spectral dependence of the deep absorptions (dotted lines) allowed the extraction of absorption thresholds at 1.8 and 2.85 eV for Trap1 and Trap2, respectively,[3] indicating that Trap1 is a mid-gap trap and that Trap2 is very deep. The same two absorptions have been associated with current collapse in the HEMT structures as well,[9] suggesting that the same HR-GaN buffer layer traps are responsible for current collapse in both devices. Photoionization spectra are shown in Fig. 1(a) for three HEMT structures, each with the HR-GaN buffer layer grown at a different pressure. The most obvious effect of growth pressure is the substantial increase in the contribution of Trap2 at the lowest pressure (65 Torr), which corresponds to higher carbon incorporation and more severe current collapse. The variations in Trap1 are less clear because of the reduced signal-to-noise ratio in that portion of the spectrum.

However, the concentrations of the relevant traps could be determined by studying the dependence of the relative drain current increase ($\Delta I/I_{\mathrm{dark}}$) on the amount of light illumination that is incident on the device, using a single, characteristic wavelength for each trap.[4] These were chosen to be

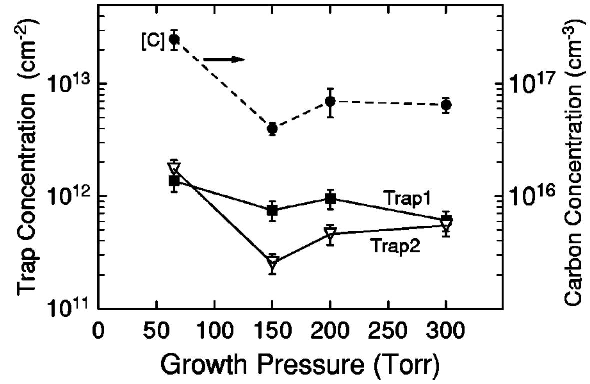

FIG. 2. The areal concentrations of the two deep traps in the HR-GaN layer, as a function of HR-GaN growth pressure, are compared to the volume concentration of carbon as measured by SIMS.

400 nm (3.07 eV) for Trap2 and 633 nm (1.96 eV) for Trap1. These results, shown as the symbols in Fig. 1(b), were measured for each trap for each of the four HR-GaN growth pressures employed. The drain current increases linearly at low light levels and saturates at high light levels, after most of the trapped charge has been released and the drain current has been restored. The data are fitted (solid lines) using a model that was developed for the GaN MESFET[4] to describe the light-induced return of the trapped charge distribution to the conducting channel. Minor adjustments made to this model to accommodate the HEMT structure are described in detail in a separate publication.[10] The two parameters that were varied during the fitting procedure were the areal trap concentration and the trap photoionization cross section. The resulting cross sections were determined to be $\approx 10^{-15}$ cm^2 for Trap2, comparable to that of the MESFET,[3] and $\gtrsim 10^{-18}$ cm^2 for Trap1, which is somewhat less (6×10^{-17} cm^2) than that of the MESFET.

In Fig. 2 the areal concentration of each trap, determined by the saturation level of ($\Delta I/I_{\mathrm{dark}}$), is plotted as a function of the growth pressure of the HR-GaN buffer layer. The uncertainty (error bars) is estimated as $\pm 20\%$. The concentration of Trap2 is seen to exhibit a sharp increase at low growth pressure, while the Trap1 concentration increases much more gradually toward lower pressures. These results are compared in the figure to the volume concentration of carbon, measured by secondary ion mass spectrometry (SIMS) for the same material. It is evident that the Trap2 concentration tracks the carbon concentration as a function of growth pressure, suggesting that Trap2 is most probably a carbon-related defect. While the Trap1 concentration does not appear to track the carbon concentration in the same way, the gradual increase toward lower pressures does correlate with the smaller grain sizes and higher dislocation densities that are seen at these pressures.[7] This suggests the possibility that Trap1 may be related to these extended defects. By plotting the trap concentrations as a function of the carbon concentration in Fig. 3, it can be seen that the concentration of Trap2 is proportional to the concentration of *empty* carbon-related defects.[11] This lends weight to the idea that Trap2 is a carbon-related center. The extrapolation of the Trap1 data to zero carbon concentration still corresponds to a significant trap concentration, which seems to support the idea that Trap1 is not carbon related.

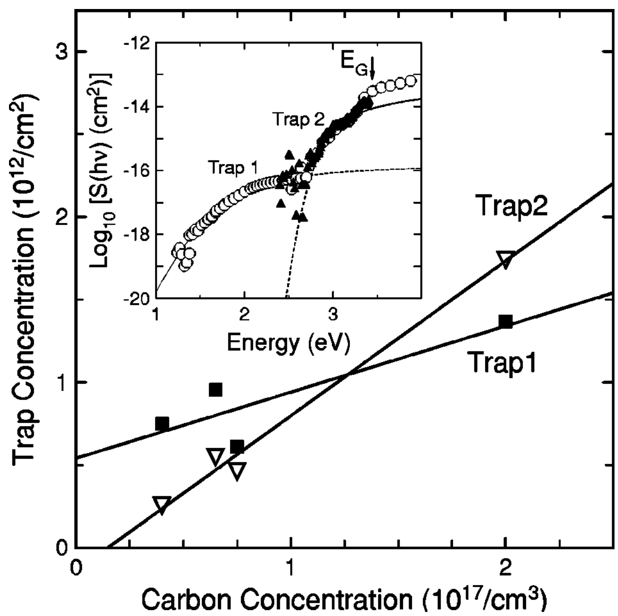

FIG. 3. The areal concentrations of the two deep traps in the HR-GaN layer, as a function of the carbon concentration in the layers. The inset shows the comparison of the Trap2 photoionization spectrum (open circles) with an absorption spectrum associated with carbon doping (filled triangles) in GaN:C, as determined by PLE measurements.

The association of Trap2 with carbon is also supported by the fact that an absorption spectrum associated specifically with carbon doping, obtained by photoluminescence excitation spectroscopy (PLE) of yellow luminescence (YL) in carbon-doped GaN,[12,13] is almost identical to the photoionization spectrum of Trap2. This is shown in the inset of Fig. 3 for the PLE data of Reuter *et al.*,[13] where the solid triangles represent the difference between the PLE spectra of carbon-doped and undoped materials, and is compared to the photoionization spectrum of Trap2 for a GaN MESFET (open circles). The excellent agreement between these spectra is strong supporting evidence that the Trap2 absorption is associated with the presence of carbon. However, it is unclear whether the carbon-related defect resides at a lattice site or is associated with extended defects.

While the idea that carbon introduces a deep acceptor level into GaN has not been firmly established, there have been a number of reports that would suggest that, under the right growth conditions, this can occur. These observations do not eliminate the possibility that HR behavior in GaN:C is achieved by some indirect process where the compensating defect does not involve carbon. However, substantial evidence for such a process has yet to be reported. In support of a deep carbon-related defect, an exhaustive study of YL in carbon-doped GaN[12] concluded that a C_N–V_{Ga} complex provided a deep acceptor level 0.86 eV above the valence band edge. Preliminary calculations by Neugebauer and Van de Walle[14] confirmed the possibility that this defect could act as a deep acceptor and, with the shallow C_N acceptor, could compensate donors in *n*-type material. Carbon doping has also led to significant reductions in the carrier concentration of *n*-type GaN,[15] and has even been employed to grow HR-GaN[16]—with HEMT devices fabricated on this material exhibiting excellent high-frequency performance.[17]

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